# Delta waves differently modulate high frequency components of EEG oscillations in various unconsciousness levels

Behnam Molaee-Ardekani, *Student Member, IEEE*, Lotfi Senhadji, *Senior Member, IEEE,* Mohammad-Bagher Shamsollahi, *Member, IEEE,* Eric Wodey, Bijan Vosoughi-Vahdat, *Member, IEEE*

**Abstract— In this paper we investigate the modulation properties of high frequency EEG activities by delta waves during various depth of anesthesia. We show that slow and fast delta waves (0-2 Hz and 2-4 Hz respectively) and high frequency components of the EEG (8-20 Hz) are correlated with each other and there is a kind of phase locking between them that varies with depth of anesthesia. Our analyses show that maximum amplitudes of high frequency components of the EEG signal are appeared in different phases of slow and fast delta waves when the concentration of Desflurane and Propofol anesthetic agents varies in a patient. There are some slight differences in using slow and fast components of delta waves. For instance, when depth of anesthesia changes, biphasic responses of the EEG have more influences on results of the fast delta wave method. In addition, this method obtains more robust and less noisy results compared with the slow delta wave method. Since phase angle between fast EEG oscillations and delta waves indicates the status of information processing in the brain and it changes in various unconsciousness levels, it may improve the performance of other classic methods of determining depth of anesthesia.**

## I. Introduction

The electroencephalogram (EEG) is a sum of different sinusoids with a fairly wide frequency spectrum. The frequency range lies between 0.3 and 70 Hz and it is classically divided to different frequency bands such as delta, theta, alpha, beta and gamma bands. When an anesthetic agent is inducted and anesthesia deepens, the EEG becomes more regular before disappearing into an isoelectric activity (burst-suppression) in very deep anesthesia. In moderate to deep anesthesia the EEG is dominated by globally coherent slow wave activity in the delta frequency range (0–4 Hz) [1].

According to Steriade and coworkers [2], the slow delta oscillations have the ability to trigger and group cortical network firing that correspond to faster activities of EEG. They observed that the hyperpolarizing phase of the depth recorded slow oscillation is associated with a global dysfacilitation in corticothalamic networks resulting in reduced neural firing. The depolarizing phase, on the other hand, was found to be accompanied by a corticothalamic facilitation of neural firing.

In this context, it has been speculated that in light anesthesia fast EEG oscillations are modulated by slow waves [3]. Fast EEG oscillations reach their maximum value when slow EEG waves are in their minimum values. This yields a negative correlation between fast oscillations and slow waves. It remained unclear, however, whether the modulation of high-frequency EEG activities by slow oscillations is independent with anesthetic drug concentration or not. In the present study, we thus examine the phase of the modulation of high frequent activities (8-20 Hz) by delta waves during different depth of anesthesia in children.

Since it has been shown that in waking periods slow (0-2 Hz) and fast (2-4 Hz) components of delta waves are differently correlated to theta, alpha and beta frequency bands [4], we divide the delta band into slow and fast components, and separately investigate the modulation of high frequency EEG activities by slow and fast delta waves.

In this study, we have used Desflurane and Propofol anesthetics to show that phase and strength of the modulation of high frequency EEG activities by delta waves vary with anesthetic concentration. Characteristics of modulation between two different brain activities may directly indicate the status of information processing in the brain; therefore they can be used as monitoring tools to indicate the status of the patient during anesthesia. Since such method of determining depth of anesthesia is established based on information processing of the brain, it may be employed beside many other *ad hoc* methods of determining depth of anesthesia such as Bispectral Index, Spectral Edge Frequency and Median Frequency [5] to improve their efficiencies.

## II. Methodology

### A. Procedure of data recording

We recorded EEG signals on 10 children 20 minutes before beginning surgical operation. Anesthesia was performed by Desflurane or Propofol agents. After intubation, different anesthetic drug concentrations were administered in stepwise manner to provide 2, 1 and 0.5

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B. Molaee Ardekani is with INSERM, U642, Rennes, F-35000, France; Université de Rennes 1, LTSI, Rennes, F-35000, France and with Sharif University of Technology, Tehran, Iran. (emails: behnam.molaee-ardekani@univ-rennes1.fr , b_molaee@mehr.sharif.edu)

L. Senhadji is with INSERM, U642, Rennes, F-35000, France and with Université de Rennes 1, LTSI, Rennes, F-35000, France. (email: lotfi.senhadji@univ-rennes1.fr)

M.B. Shamsollahi and B. Vosoughi Vahdat are with BiSIPL, School of Electrical Engineering at Sharif University of technology, Tehran, Iran. (emails: mbshams@sharif.edu , vahdat@sharif.edu)

E. Wodey is with INSERM, U642, Rennes, F-35000, France; Université de Rennes 1, LTSI, Rennes, F-35000, France and with CHU, Department of anesthesia Rennes, F-35000, France. (email: eric.wodey@chu-rennes.fr)

MAC (Minimum Alveolar Concentration) respectively. In order to stabilize EEG signal for each desired MAC, we resumed drug administration for each given drug concentration for about 10 minutes. Figure 1 depicts the diagram of the input desired concentration.

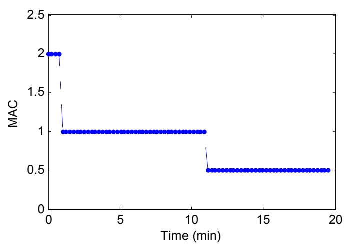


Figure 1: After intubation concentrations of anesthetic agents are changed in stepwise manner from 2 to 0.5 MAC.

### B. *Signal analysis*

EEG recordings were pre-processed by a high-pass finite impulse response (FIR) filter. The passband and stopband of this filter were 0.2 and 0.02 Hz respectively. Slow delta wave were extracted from the pre-processed EEG (see figure 2 and 3) with a low-pass FIR filter with 2 Hz passband and 2.3 Hz stopband. To extract the fast delta wave and fast EEG oscillations, we used a band-pass FIR filter. The passbands and stopbands of the first filter were equal to 1.8, 3.6, 2.1 and 4 Hz. These parameters were 7, 20, 8 and 25 Hz for the second filter.

The modulation between delta waves and fast EEG oscillations was quantified as follows:

1) Slow or fast EEG delta waves were segmented to 30 seconds 50 percent overlapped epochs, and their energies were normalized to one. The analytic signal of each epoch, which is a complex signal, was calculated. The real part of the analytic signal is equal to the EEG epoch and the imaginary part is the Hilbert transform of the EEG epoch. The modulus and angle of the thereby obtained complex signal represent the amplitude and phase of slow or fast delta waves.

2) Amplitude of fast EEG oscillations were also calculated as the above described method for slow and fast delta waves

3) Amplitudes of fast EEG oscillations were sorted to 70 bins according to their corresponding values of slow or fast delta phases (See figure 2E). Such procedure could also be done for amplitude values of slow or fast delta waves.

4) The average of amplitude values of fast EEG oscillations (or delta amplitudes) was calculated in each bin. Then the mean value of all 70 bins was subtracted from the result to have a zero mean 70-points signal (see figure 4). From then, this signal is referred to as modulation signal.

## III. Results and Discussions

### A. *Anesthesia shifts the phase of modulation signal*

In different depth of anesthesia, a modulation exists between delta waves and fast EEG oscillations (We selected 8 to 20 Hz interval as the frequency band of fast EEG oscillations because higher frequencies are not significant in children). In another word, modulation signals (MS) are not flat lines in different depth of anesthesia. Surprisingly, not only MS are not flat, but also their extremum positions change by anesthetic concentration. It means that the maximum amplitude of fast EEG oscillations happens in different phases of delta waves. This phase is referred to as phase of modulation signal. It can be said that delta waves and fast EEG oscillations are two phased-locked activities in which their phase differences are changed by anesthetic concentrations.

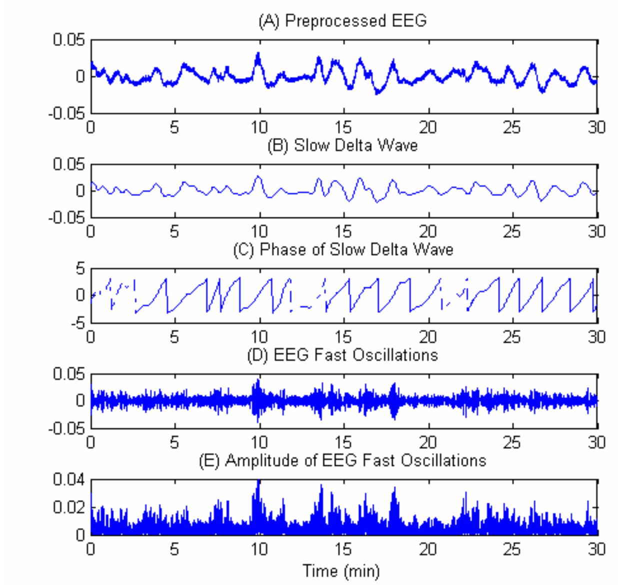


Figure 2: A pre-processed 30 s EEG epoch (A). Slow component of EEG delta band (0-2 Hz) (B). Phase of the delta wave which is calculated from the analytic signal. Dashed line does not participate in further signal analyses because there are more than 3 extrema between $-\pi$ and $+\pi$ radians (C). High frequency oscillations of the EEG signal (8-20 Hz) (D). Amplitudes of the high frequency oscillations of the EEG signal (E).

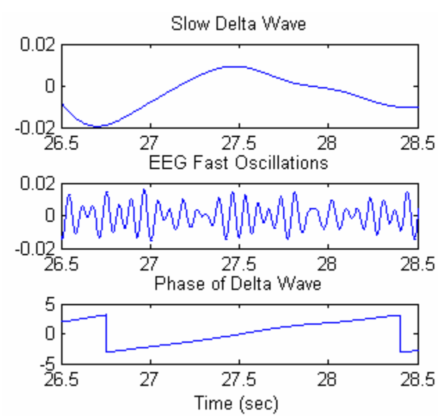


Figure 3: Enraged shape of depicted EEG delta wave, delta phase and fast oscillations in figure 2 between 26.5 s and 28.5 s.

Figure 4 depicts amplitude values (in 70 bins) of fast EEG oscillations versus phase of slow delta wave for three EEG epochs in 0.5, 1 and 2 MAC. We refer to these MS's as slow modulation signals (SMS) (blue dotted lines). For comparison we have also shown amplitude values of slow delta wave versus phase of slow delta wave (red x marks). In low anesthetic drug concentration (*i.e.* 0.5 MAC), the maximum amplitude of SMS occurs around $\pm\pi$ radians. In such case, a sinusoid function can be fitted to SMS. Increasing the drug concentration to 1 MAC causes appearance of two peaks around +2 radians and –1 radian. Typically the amplitude of the peak which is around +2 radians is higher than the other one. In order to properly fit a sinusoid function to these graphs, we have to increase the frequency of the sinusoid function to 2 Hz (dashed line curve in the figure). In deep anesthesia, a single peak is observed between -2 to +1 radian. Comparison of these SMS shows that the phase of SMS moves to a lower values by increasing of drug concentration. Similar results are obtained for phase of fast modulation signals (FMS).

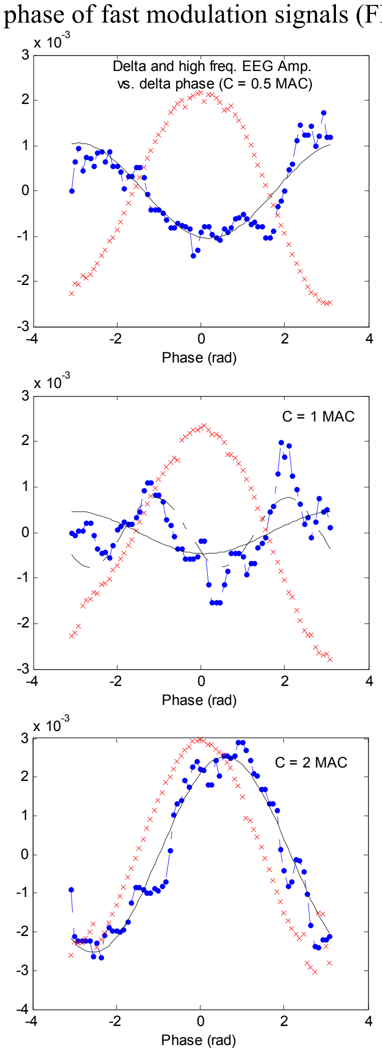


Figure 4: Amplitudes of fast EEG oscillations versus phase of slow delta wave for three EEG epochs in 0.5, 1 and 2 MAC (blue dotted lines) and amplitudes of slow delta wave versus phase of slow delta wave (scaled 20%, red x marks). In each case, a sinusoid function has been fitted to fast EEG oscillations. In C = 1 MAC, a 2 Hz sinusoid function provide a better matching.

Such SMS and FMS were obtained for all EEG epochs of the 10 patients who participate in our 20 minutes EEG recordings. Figure 5 and 6 (top) illustrate SMS and FMS graphs of a same patient in gray-level format during the 20 minutes of the EEG recording respectively.

### *B. Phase locking can be tracked by fitting a 2D function to SMS or FMS*

In order to track the delta phase in which the maximum amplitude of fast EEG activity occurs, a 2D function is first fitted (figure 5 and 6 bottom) to 2D data points of SMS or FMS (figure 5 and 6 top). Such 2D data fitting smoothes 2D SMS and FMS in phase and time domains and also enables us to be able to better track the slow or fast delta phases because they do not change vary fast in time domain.

The following 2D functions were selected to be fitted with 2D data points of SMS or FMS to find the best function for this purpose. The shapes of one-dimensional SMS (and FMS) in figure 4 were the main motivation factors in selecting the following functions:

$$F_1(t,\varphi) = A(t)\cos(2\pi\varphi - \phi(t))$$

$$F_2(t,\varphi) = A(t)\left(1-(\varphi-\phi(t))^2\right)\exp\left(-(\varphi-\phi(t))^2/2\right)$$

$$F_3(t,\varphi) = A_1(t)\left(1-(\varphi-\phi_1(t))^2\right)\exp\left(-(\varphi-\phi_1(t))^2/2\right) + A_2(t)\left(1-(\varphi-\phi_2(t))^2\right)\exp\left(-(\varphi-\phi_2(t))^2/2\right)$$

where $A(t)$ and $\phi(t)$ are polynomial functions:

$$A(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3, \quad \phi(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3$$

Analyses show $F_3(t,\varphi)$ has the most capability to be fitted with 2D graphs because it is consisted of two Mexican hats that their amplitudes $A_{1,2}(t)$ and centers $\phi_{1,2}(t)$ are tuned separately in time domain. Since $F_3(t,\varphi)$ consists of two independent Mexican hats, it is also convenient to be fitted with the graphs that have two separate peaks (*e.g.* see the SMS graphs corresponding to 1 MAC in figure 4).

### *C. SMS and FMS: A comparison*

In order to respond to this question that "is there any difference between the phase locking of slow and fast delta waves and fast EEG oscillations", we obtained 2D SMS and FMS of the patients and tracked their phases. Both methods show that the phase diagram of SMS and FMS varies by changing the anesthetic concentration. However there are some points that should be mentioned here.

Figure 5 depicts a 2D SMS and its fitted surface (*i.e.* tuned $F_3(t,\varphi)$) in gray-level. Since EEG epochs are overlapped 50%, the time resolution of the 2D SMS is 15 seconds. The maximum amplitude of each row of the fitted surface and its corresponding slow delta phase (i.e. phase of SMS) are plotted in figure 7. Figures 6 and 8 are duals of figures 5 and 7 considering that slow delta wave has been replaced by fast delta wave.

In general, SMS are noisier than FMS so phase tracking of FMS provide more robust and clearer results. The difference between maximum and minimum values of SMS is low and their positions vary a lot in consecutive EEG epochs. This can be better understood by obtaining the histograms of 2D SMS and FMS of the patients. Figure 9 (left side) illustrates the histogram of FMS values. This histogram is wider than the SMS histogram in the right side and indicates that extermums of FMS are more distinguishable from rest of signal.

When a drug concentration is changed rapidly (*e.g.* from 2 MAC to 1 MAC) a biphasic response is observed on EEG signals [6, 7]. Transition the depth of anesthesia from one level to another level is basically accompanied by a delayed transient increase of high frequency EEG amplitudes that are disappeared after a few minutes. Basically, classical measuring methods predict a lower depth of anesthesia during biphasic response. During biphasic response, phase diagrams of FMS show slightly decrease in depth of anesthesia, but phase diagrams of SMS do not influenced by biphasic response. A comparison between top graphs in figures 7 and 8 shows that decrement of the depth of anesthesia (according to the illustrated protocol in figure 1) is accompanied by monotonic increase of the phase diagram of SMS in figure 7, but there are two local maximums on the phase diagram of FMS around 4 and 16.5 minutes that are related to biphasic response.

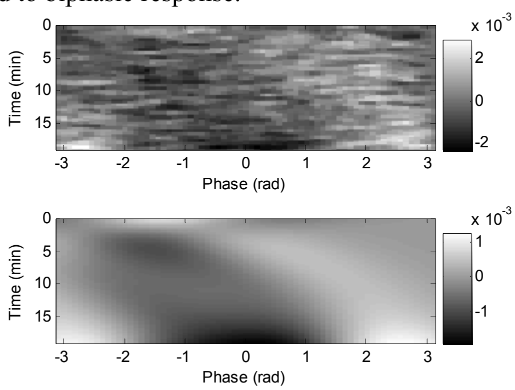


Figure 5: Two-dimensional SMS (top) and its fitted surface by $F_3(t,\varphi)$ (bottom) in gray-level. SMS graphs are related to a patient during the 20 minutes of EEG recordings before surgical operation.

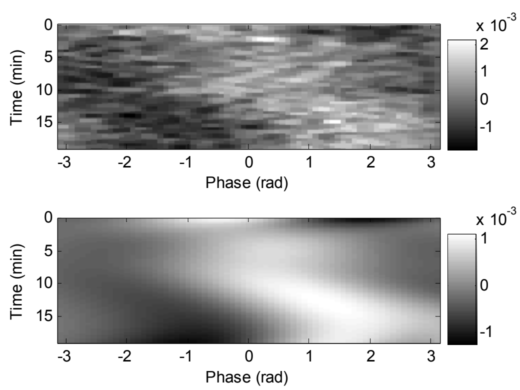


Figure 6: Two-dimensional FMS (top) and its fitted surface by $F_3(t,\varphi)$ (bottom) in gray-level. FMS graphs are related to the same patient described in figure 5.

Generally, during rapid changes of anesthetic drug concentrations the strength of phase locking between fast/slow delta waves and fast EEG oscillations is reduced. This can be understood by inspecting the maximum amplitudes of SMS or FMS depicted in bottoms of figures 7 and 8. Local minimums of these two figures are basically concurrent with rapid changes of drug concentrations especially from 2 MAC to 1 MAC.

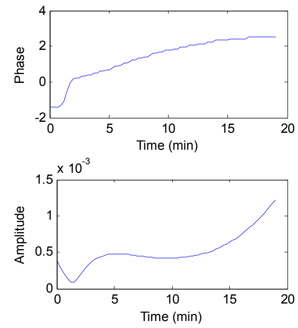


Figure 7: Phase diagram of SMS (top) and its corresponding amplitude diagram (bottom) of the patient whose 2D SMS has been illustrated in figure 5.

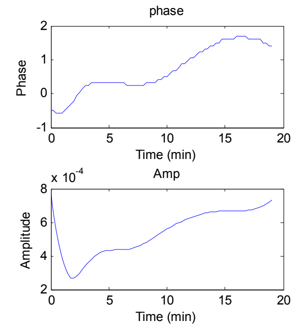


Figure 8: Phase diagram of FMS (top) and its corresponding amplitude diagram (bottom) of the patient whose 2D FMS has been illustrated in figure 6.

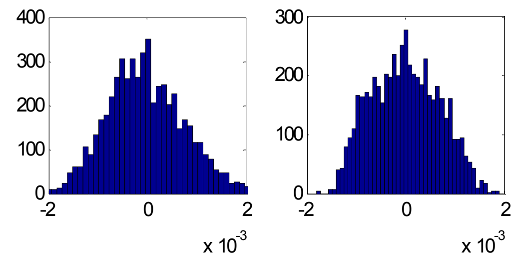


Figure 9: Histograms of the amplitude values of fast oscillations vs. fast (left) and slow (right) delta waves. Fast delta waves provide better distinguishable extremums in the amplitude values of fast oscillations (left histogram is wider compared with the other histogram)

## IV. Conclusion and Suggestion

Slow and fast delta waves modulate fast EEG oscillations. The phase of modulation is a function of anesthetic drug concentration (it varies from almost -2 radian to $\pi$ radian) so it may be used as a tool for monitoring unconsciousness level. Modulation between slow delta waves and fast EEG oscillations are noisier than the modulation between fast delta waves and fast EEG oscillations.

## References

[1] Constant, I., R. Seeman, and I. Murat, *Sevoflurane and epileptiform EEG changes.* Paediatr Anaesth, 2005. **15**(4): p. 266-74.

[2] Steriade, M., F. Amzica, and D. Contreras, *Synchronization of fast (30-40 Hz) spontaneous cortical rhythms during brain activation.* J Neurosci, 1996. **16**(1): p. 392-417.

[3] Burkitt, A.N., H. Meffin, and D.B. Grayden, *Study of neuronal gain in a conductance-based leaky integrate-and-fire neuron model with balanced excitatory and inhibitory synaptic input.* Biol Cybern, 2003. **89**(2): p. 119-25.

[4] Benoit, O., A. Daurat, and J. Prado, *Slow (0.7-2 Hz) and fast (2-4 Hz) delta components are differently correlated to theta, alpha and beta frequency bands during NREM sleep.* Clinical Neurophysiology, 2000. **111**(12): p. 2103-2106.

[5] Senhadji, L., E. Wodey, and E. Claude, *Monitoring approaches in general anesthesia: a survey.* Crit. Rev. Biomed. Eng., 2002. **30**(1-3): p. 85-97.

[6] Kuizenga, K., C.J. Kalkman, and P.J. Hennis, *Quantitative electroencephalographic analysis of the biphasic concentration-effect relationship of propofol in surgical patients during extradural analgesia.* Br J Anaesth, 1998. **80**(6): p. 725-32.

[7] Kuizenga, K., J.M. Wierda, and C.J. Kalkman, *Biphasic EEG changes in relation to loss of consciousness during induction with thiopental, propofol, etomidate, midazolam or sevoflurane.* Br J Anaesth, 2001. **86**(3): p. 354-60.